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The Surface Circulation of the Balearic Sea

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Until recently, the surface circulation of the Balearic Sea has been viewed as largely cyclonic with a fairly quiescent central dome. However, recent studies involving ship data, tracked drifters, current meter moorings, and satellite imagery indicate that this sea has strong mesoscale variability and a more complex general circulation. These studies, together with an examination of registered satellite imagery collected during the Western Mediterranean Circulation Experiment (WMCE), indicate that the surface circulation is strong year-round, and characterized by two permanent density fronts located on the continental shelf slope (the Catalan Front) and the Balearic Islands shelf slope (the Balearic Front). The Catalan Front is the more active of the two fronts. In the northern area, a plume of cold water is frequently observed moving southward along the continental slope region, shedding dipole eddies along the leading edge of the plume. In addition, the Catalan Front continuously spawns energetic filaments that appear to be associated with the plume of cool water. The likely mechanism of formation of these filaments is the deflection of the cold water by the regional submarine canyons.

1. Introduction

The Balearic Sea lies in the northwestern Mediterranean Sea between the Iberian coast and the Balearic Islands (Ibiza, Mallorca, and Menorca). For this study, we examine the area (also called the Catalan Sea) defined by a northern limit at 42°30′N, a southern limit at 38°45′N, and 4°0′E as the eastern limit north of Menorca (Figure 1). Most of the area is less than 2000 m deep and is closed to outside access below 1000 m except north of Menorca. The continental and island shelf regions are generally narrow (less than 25 km). North of Tarragona (41°N), the continental shelf is repeatedly bisected by a number of submarine canyons. From Tarragona south to Castello (40°N), the shelf widens to a distance of approximately 60 km. We will show that the regional topography, especially the shelf slope, plays an important role in the regional circulation.

Salat and Cruzado [1981] and *Salat and Font* [1987] have presented Balearic Sea hydrographic data that show that the horizontal temperature gradients in the surface layer are weak in comparison to the strong spatial changes of salinity. This difference is especially marked in winter. They indicate two definable seasons: the well-mixed period of winter and the more stratified period of summer. The actual time and strength of the transition periods (spring and fall) vary from year to year. Spring, characterized by the flushing of the Rhone River into the Gulf of Lyon and the Ebro onto the Iberian shelf, displays strong variations in the coastal water salinity. *Castellon et al.* [1985] have described the strengthening of the surface density gradients that result at this time.

In 1986 a series of field experiments were conducted to define the general circulation of the western basins of the Mediterranean Sea. The field results of this experiment, the Western Mediterranean Circulation Experiment (WMCE) [*La Violette*, 1987], prompted a reexamination of oceanographic data collected in the Balearic Sea. This study on the surface circulation of this sea is part of the result of the WMCE.

2. Recent Studies

Previous studies of the western Mediterranean Sea have provided general descriptions of the Balearic Sea [e.g., *Ovchinnikov*, 1966]. The circulation in these early studies is presented as a single, large oblong cyclonic cell with a central axis (divergence zone) aligned with the shape of the basin. Studies of the sea itself [e.g., *Font and Miralles*, 1978] also show a cyclonic circulation about one or more central thermohaline domes. However, the recent accumulation of more closely spaced ship data, as well as data gathered from a variety of other sources (drifters, current meters, and satellite imagery), has provided a new view of higher temporal and spatial variability in the circulation of the sea.

Font et al. [1988] described two large permanent density fronts in the Balearic Sea. One was located on the continental shelf slope (which they called the Catalan Front). A second, distinctly separate, front was located over the Balearic Islands shelf slope (which they called the Balearic Front). Other recent studies have shown that the two fronts are well defined and that one, the Catalan Front, has rapidly evolving eddies and shelf slope filaments associated with it. Using satellite imagery and drifter data, *Wang et al.* [1988] detected rapid flow reversals induced by one such filament

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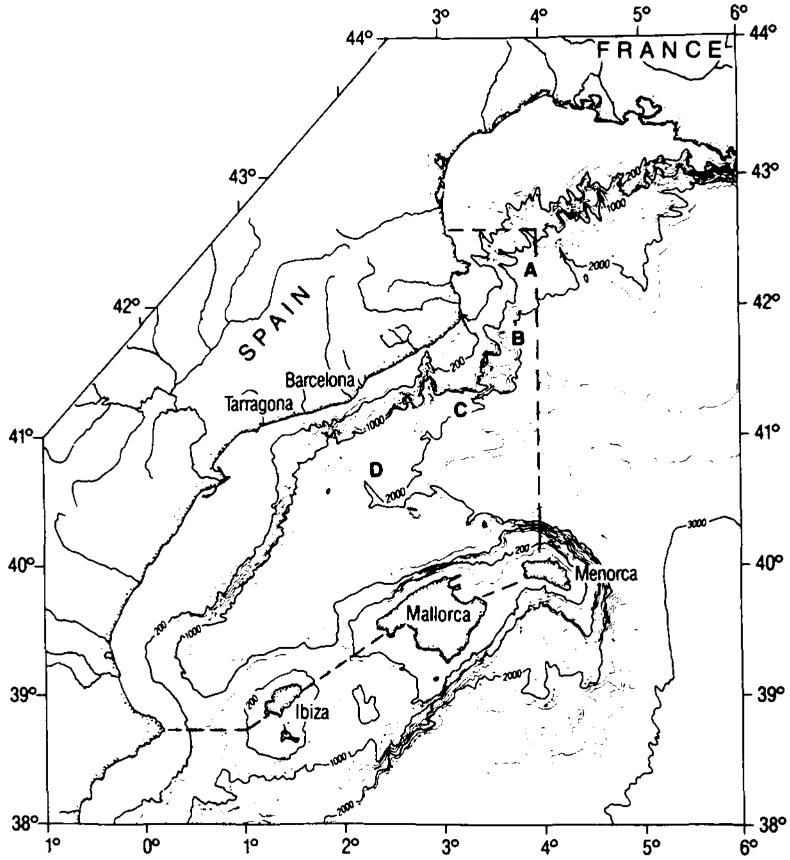

Fig. 1. Regional topographic features of the Balearic (Catalan) Sea.

(Figure 2). Long-term current meter measurements in the slope region near the Ebro River show the repeated occurrence of several-day reversals in the southwestward alongshore flow at 8-, 50-, and 100-m depths [*Font*, this issue].

Maso [1989] found modifications to the flow in the Catalan Front which appear to have been induced by submarine canyons located in the narrow shelf north of Tarragona (the canyons marked A–D in Figure 1). They found that the canyons act as deflecting barriers to the southward flow, inducing an offshore flow on the southern side of each canyon.

Although these studies individually provide information on local phenomena, they provide even more information when examined as a group. They indicate that the Catalan and Balearic frontal systems constitute the main features of the surface circulation within the basin. These studies were limited in both time and space, and several broad questions were left unanswered: What are the temporal scales of the mesoscale frontal instabilities? What are the spatial scales? How do the mesoscale features interact with one another? For some answers to these questions, we coalesce the information provided by these intensive studies with an extensive examination of satellite thermal imagery.

3. Satellite Thermal Imagery

The Data

As stated by *Salat and Cruzado* [1981], the greatest variations in the thermohaline structure of the region are those associated with changes in salinity. However, proper interpretation of the thermal patterns in satellite infrared imagery may be used as reasonable tracers of the flow. Thus, although seasonal variations in the strength of the circulation (resulting from seasonal variations in salinity) are not readily shown, the thermal imagery clearly shows the surface circulation patterns. The satellite images used in this study are from the NOAA advanced very high resolution radiometer (AVHRR). They have been enhanced and mapped into Mercator projections (see *La Violette* [1988] for further rationale of the circulation pattern/flow relationship as well as the general image processing methodology).

Most of the satellite data are from the year of the WMCE (November 1985 to November 1986). Examination of satellite imagery from other years indicates that typical circulation patterns were observed during the WMCE year. Image series covering different time scales (day, week, and month, clouds and data permitting) were examined to derive the displacement and evolution of surface features. Table 1 presents a listing of the imagery examined.

Because of the generally weak thermal contrast in most of the Mediterranean outside the Alboran Sea, the normal process of combining two channels of the NOAA AVHRR to give actual temperature values could not be used effectively [*La Violette and Holyer*, 1988]. The infrared images used here are from AVHRR channel 4 and thus present relative rather than absolute temperature values (relative accuracy of 0.2°C). The satellite image in Figure 2 is a good example of

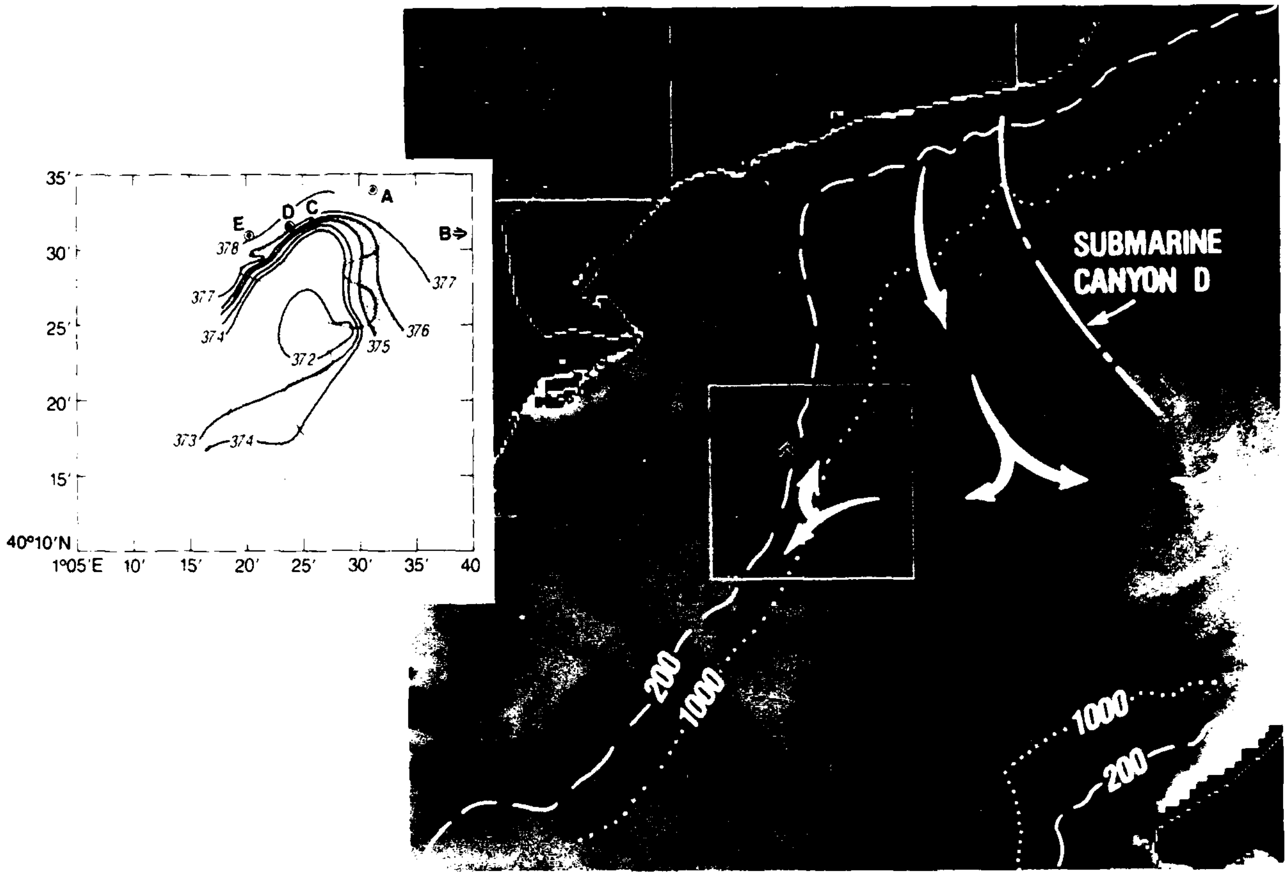

Fig. 2. Drift movements associated with a frontal filament related to submarine canyon D. The inset salinity chart for June 11, 1986, shows the position of five drifters in the active edge of one arm of a dipole eddy that forms part of the filament. This may be compared with the drifter's previous day positions (inverted Vs) in the June 10 NOAA AVHRR thermal image. The arrows in the image indicate inferred flow direction as indicated by several successive-day images. The units in the inset chart are practical salinity units. The bathymetric contours are in meters (adapted from *Wang et al.* [1988]).

the details in the surface thermal field detectable with the AVHRR channel 4.

Long-Term Satellite Studies

Representative AVHRR thermal imagery for each month in the WMCE year (Figure 3) complement recent in situ data analyses. The synoptic imagery suggest that the flow does not describe a continuous cyclonic gyre around the Balearic Sea. The patterns in the December, February, March, and October examples (the other examples in the figure are cloudy in the south) indicate that water over the shelf slope of the Spanish mainland continues southward over the sill between Ibiza and the Spanish mainland. The southward continuity of the flow and the separate circulation along the northern coast of the Balearic Islands are better seen in Figure 4.

Another important feature noticeable in the imagery is an alongshore plume of cool water entrained in the southward circulation associated with the Catalan Front (Figure 5). This cool water appears to originate outside the study area, either in the Gulf of Lyons or farther east in the Ligurian Sea. Dipole eddies are common features in this front. They are observable in the plume in August, September, and October in Figure 3 and also in Figures 2 and 5.

A third aspect is the strong control the regional bathymetry appears to have on the circulation. This was obvious in all of the imagery examined. In the Catalan Front, filament outbreaks were associated with the submarine canyons located in the narrow shelf region north of Tarragona (e.g., Figures 2, 3, 7, and 8).

Although visible throughout the imagery data set, the Balearic Front was not always well defined. Figure 6 shows good examples of this front. Other examples can be seen in Figure 3 (e.g., March, April, May, June, and September). Examination of the WMCE thermal imagery set showed that the boundary thermal gradient was strongest in July.

Short-Term Satellite Studies

The most continuous clear-sky conditions occur in the May data. In the slope region northeast of the canyon D filament, the displacement of small, warm features embedded in the cold water plume was monitored over several days and compared with the speed of the leading edge of the filament. The features in Figure 7 were tracked for 4 days (May 9–12). Their speed averaged 30 cm/s as they neared, and finally became entrained, in the canyon D filament. Although the entire filament was moving, especially its leading edges, this motion was considerably less than the

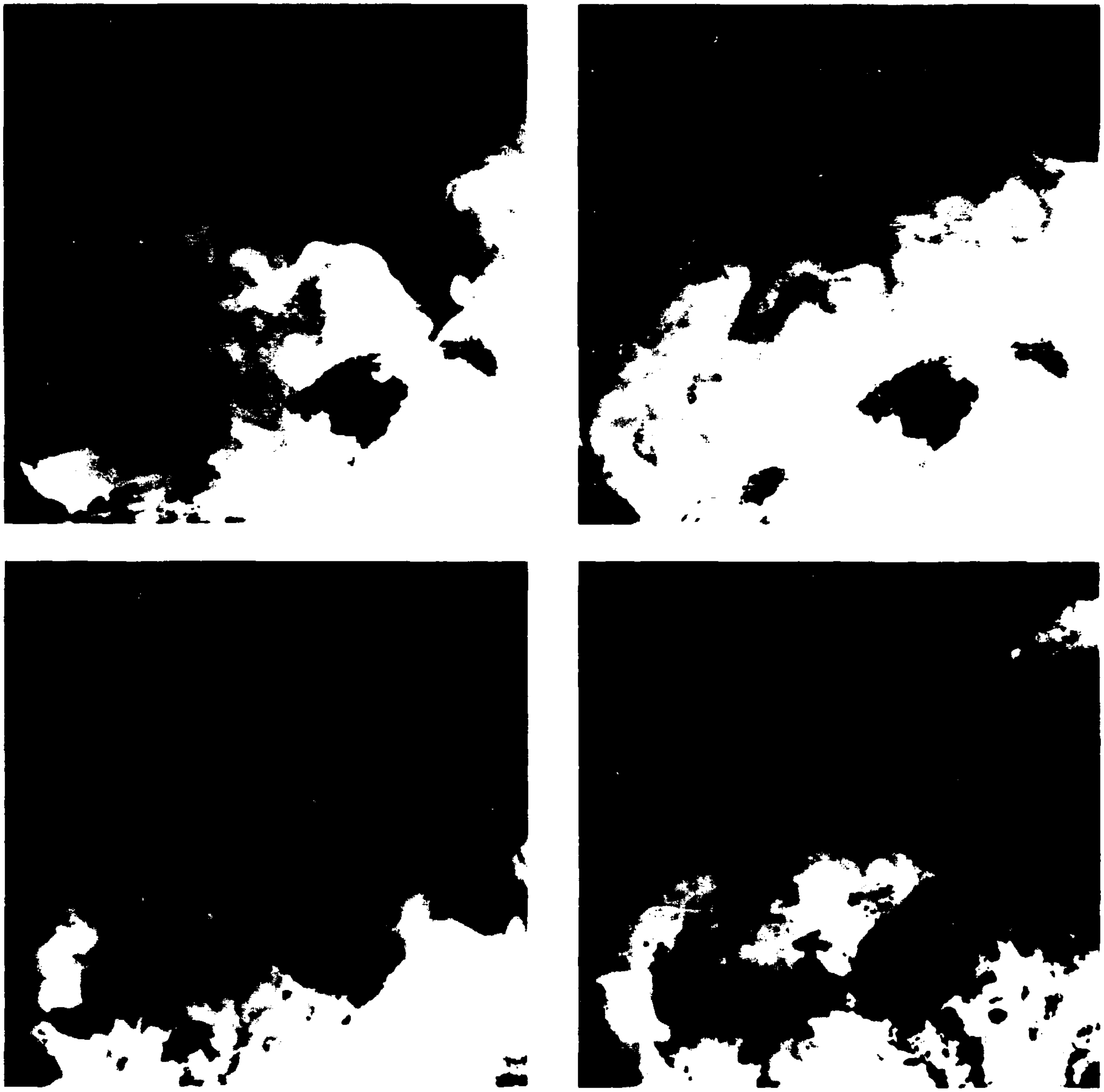

Fig. 3. Representative NOAA AVHRR thermal imagery for each month in 1986. In these and in the other imagery presented in this study, the darker areas are the colder radiated temperatures of the scene (areas that are completely black are clouds); lighter areas are warmer temperatures.

speed of the internal features. An examination of identifiable features in the warmer water showed only slight movement in comparison with the speed of the features within the [illegible] and the filament.

The boundary of the Balearic Front was commonly a wavelike structure (Figure 6). However, examination of two series of successive images covering periods of 5 days or more (one set in May and one set in June) showed little motion in the front.

4. DISCUSSION

The unique capability of satellite imagery to provide broad spatial and temporal information complements the high-resolution sampling of the recent in situ data studies. Thus the imagery involved in this study provide some answers to the questions posed in the review of recent studies given in section 2.

The continuity of the imagery proves conclusively that the regional surface layer circulation is controlled by two permanent density fronts as proposed by *Font et al.* [1988] using comparatively limited in situ data. In the satellite imagery, the Catalan Front appears throughout the year, with the weakest gradients occurring in winter. Note that the weak winter gradient may be a seasonal artifact due to the more uniform water temperatures of winter. They are not an indication of the strength of flow (indeed, as the salinity

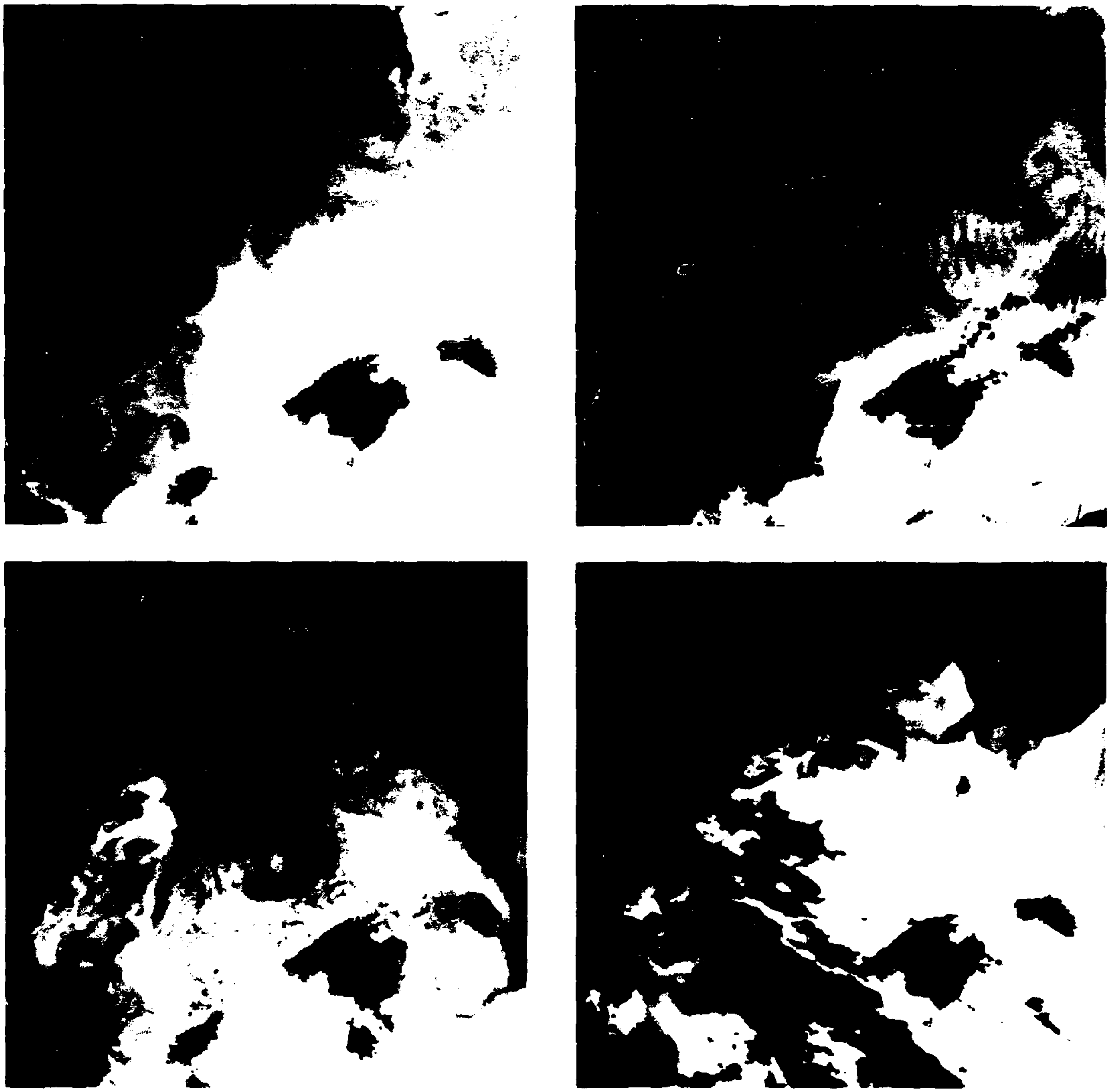

Fig. 3. (continued)

changes are greater in winter, the flow may be greater during this period). Although the thermal effect on the density structure is small in comparison with salinity, the year-round presence of strong thermal gradients is a good indication of a comparatively strong year-round surface flow. This is also in agreement with *Font* [this issue], who showed, using 4 years of current meter data, that the shelf slope current was strong throughout the year.

The satellite imagery further indicate that, although the two fronts remain in the same general positions, the Catalan Front exhibited the stronger variability. The dipole eddies repeatedly observed in the plume of cool water embedded in the Catalan Front indicate the energetics involved in the flow (e.g., Figure 2 and the August, September, and October imagery in Figure 3). Warm parcels moving inside the plume of cool water advected by the currents seem to move more rapidly than parcels outside the plume (Figure 7). In the study by *Wang et al.* [1988], satellite imagery also showed a dipole eddy that was rapidly moving and was indicated by the drifter data to be very energetic. *Tintoré et al.* [this issue] also showed the southward translation of the plume (25 cm/s) with more active internal energy exchanges taking place. *Ahlnäs et al.* [1987], in a study of dipole eddies, also suggested that these instabilities are indicative of energetic flow.

Cross-frontal filaments similar to the filaments visible in the imagery shown here have been extensively reported in other regions, for example, in the South Atlantic Bight [*Brooks and Bane*, 1983], the California coast [*Davis*, 1985], and the Mid-Atlantic Bight [*Houghton et al.*, 1986]. These frontal filaments and eddies are thought to play an important role in the exchange of shelf and slope water. However, the

TABLE 1. NOAA 6 and 9 AVHRR Imagery of the Balearic Sea Examined for This Study

Date	NOAA Satellite	Orbit No.	Start Time
	1985		
Nov. 1	9	4569	0142
Nov. 4	9	4608	0251
Nov. 8	6	33103	1650
Nov. 8	9	4664	0207
Nov. 9	9	4685	1330
Nov. 9	9	4678	0120
Nov. 9	9	4679	0338
Nov. 23	6	33318	1910
Nov. 24	6	33331	1706
Nov. 30	9	4975	0239
Dec. 3	9	5017	0207
Dec. 7	9	5066	1344
Dec. 13	9	5158	0200
Dec. 21	9	5271	0216
	1986		
Jan. 1	9	5426	0237
Jan. 1	9	5433	1402
Jan. 6	9	5504	1457
Jan. 7	9	5518	1440
Jan. 9	9	5339	0253
Jan. 9	9	5546	1423
Jan. 10	9	5553	0241
Jan. 11	9	5567	0152
Jan. 14	9	5617	1539
Jan. 15	9	5624	0251
Jan. 17	9	5659	1438
Jan. 19	9	5680	0207
Jan. 22	9	5729	1345
Jan. 27	6	34236	0639
Jan. 28	9	5807	0212
Feb. 2	9	5878	0337
Feb. 5	9	5921	0444
Feb. 7	9	5948	0244
Feb. 12	9	6019	0331
Feb. 12	9	6026	1532
Feb. 13	9	6033	0330
Feb. 19	9	6124	1347
Feb. 20	9	6131	0204
Feb. 22	9	6160	0325
Feb. 23	9	6174	0314
Feb. 23	9	6180	1335
Feb. 23	9	6181	1445
Feb. 24	9	6194	1248
Feb. 24	9	6195	1434
Feb. 26	9	6216	0243
March 2	9	6279	1401
March 2	9	6280	1541
March 3	9	6286	0148
March 3	9	6293	1322
March 4	9	6308	1444
March 5	9	6315	0308
March 6	9	6420	1355
March 12	9	6414	0334
March 12	9	6421	1610
March 14	9	6442	0312
March 14	9	6449	1443
March 15	9	6463	1432
March 16	9	6470	0251
March 20	9	6534	1555
March 22	9	6561	1348
March 22	9	6562	1528
March 24	9	6583	0306
March 24	9	6590	1437
March 25	9	6597	0255
March 27	9	6625	0233
March 28	9	6639	0223
March 29	9	6653	0212
March 29	9	6660	1338
March 30	9	6667	0201
March 30	9	6674	1403

TABLE 1. (Continued)

Date	NOAA Satellite	Orbit No.	Start Time
	1986 (continued)		
March 31	9	6681	015?
March 31	9	6682	0331
March 31	9	6688	1353
March 31	9	6689	1339
April 1	9	6696	0321
April 2	9	6716	1335
April 4	9	6738	0249
April 8	9	6802	1553
April 9	9	6809	0336
April 9	9	6816	1537
April 13	9	6872	1419
April 15	9	6900	1357
April 16	9	6914	1346
April 19	9	6957	1456
April 20	9	6971	1446
April 21	9	6985	1434
April 25	9	7041	1351
April 28	9	7084	1500
April 29	9	7097	1355
April 29	9	7098	1450
April 30	9	7112	1430
May 1	9	7119	0301
May 1	9	7125	1322
May 2	9	7133	0251
May 2	9	7140	1417
May 3	9	7147	0240
May 4	9	7161	0230
May 4	9	7168	1356
May 5	9	7175	0216
May 5	9	7182	1344
May 5	9	7183	1600
May 6	9	7189	0207
May 7	9	7204	0339
May 7	9	7211	1530
May 8	9	7218	0328
May 8	9	7225	1529
May 9	9	7232	0317
May 9	9	7239	1443
May 10	9	7246	0306
May 10	9	7253	1432
May 11	9	7260	0255
May 11	9	7267	1421
May 12	9	7274	0244
May 12	9	7281	1410
May 13	9	7288	0233
May 13	9	7295	1359
May 14	9	7302	0222
May 14	9	7309	1349
May 15	9	7316	0212
May 15	9	7323	1338
May 16	9	7337	1327
May 17	9	7352	1458
May 18	9	7366	1447
May 19	9	7380	1436
May 20	9	7394	1425
May 21	9	7408	1405
May 22	9	7415	0238
May 22	9	7422	1354
May 24	9	7450	1332
May 25	9	7457	0205
May 25	9	7464	1321
May 25	9	7456	1503
May 27	9	7485	0143
May 27	9	7493	1442
May 28	9	7500	0314
May 28	9	7507	1431
May 30	9	7535	1419
May 31	9	7549	1358
June 2	9	7577	1347
June 3	9	7591	1329
June 4	9	7599	0340
June 5	9	7612	0147

TABLE 1. (Continued)

Date	NOAA Satellite	Orbit No.	Start Time
	1986 (continued)		
June 5	9	7613	0329
June 5	9	7620	1455
June 6	9	7627	0318
June 8	9	7655	0257
June 8	9	7662	1423
June 9	9	7669	0246
June 9	9	7676	1413
June 10	9	7690	1401
June 11	9	7697	0224
June 12	9	7712	0354
June 13	9	7732	1320
June 14	9	7740	0333
June 16	9	7768	0312
June 16	9	7775	1438
June 17	9	7782	0301
June 17	9	7789	1427
June 18	9	7796	0250
June 22	9	7853	0348
June 27	9	7923	0255
June 28	9	7937	0244
July 5	9	8036	0232
July 9	9	8092	0148
July 15	9	8177	0255
July 18	9	8219	0152
July 23	9	8290	0240
Aug. 19	9	8671	0253
Aug. 23	9	8727	0209
Sept. 2	9	8868	0202
Sept. 4	9	8896	0141
Sept. 10	9	8981	0217
Oct. 10	9	9404	0157
Oct. 28	9	9658	0205
Oct. 30	9	9687	0325
Nov. 3	9	9743	0242
Nov. 11	9	9856	0257
Nov. 24	9	10046	1412

The study region was not cloud free during a considerable period of this time (~ 50%). Also, the individual areas were sometimes cloudy, whereas others were not.

physical processes which lead to the water exchange remain poorly understood.

The imagery show the thermal contrast of the Balearic Front is strongest in summer. The wavelike appearance of the Balearic Front (Figure 6) is similar to that noted in other studies of active frontal systems. For example, *La Violette* [1983] found such waves moving at speeds of 70 cm/s in the frontal region of a large eddy actively being shed from the Labrador Front. In the Balearic Front, however, the wavelike features gave no evidence of lateral movement.

The satellite thermal imagery shows that features similar to those visible in the Balearic Sea are also found in other parts of the northwestern Mediterranean. Note, for example, the continuity of the coastal frontal features in the sample thermal image in Figure 8. Such effects emphasize that the surface circulation of the sea is not isolated from the other basins but is an integral part of the total circulation of the region.

5. Conclusions

In this paper, we coalesced spatially and temporally limited information provided by recent in situ data analyses with a study of satellite imagery obtained during the WMCE year, to derive the major features of the surface circulation of the Balearic Sea.

We have derived several conclusions from this combination.

1. A permanent thermohalinic dome in a sea that is free of major dynamical features is no longer a viable premise. Instead, the statement by *Font et al.* [1988] that the regional surface layer circulation is controlled by two permanent density fronts (the Catalan and Balearic fronts) seems to be more correct.

2. The Catalan Front is present year-round and appears

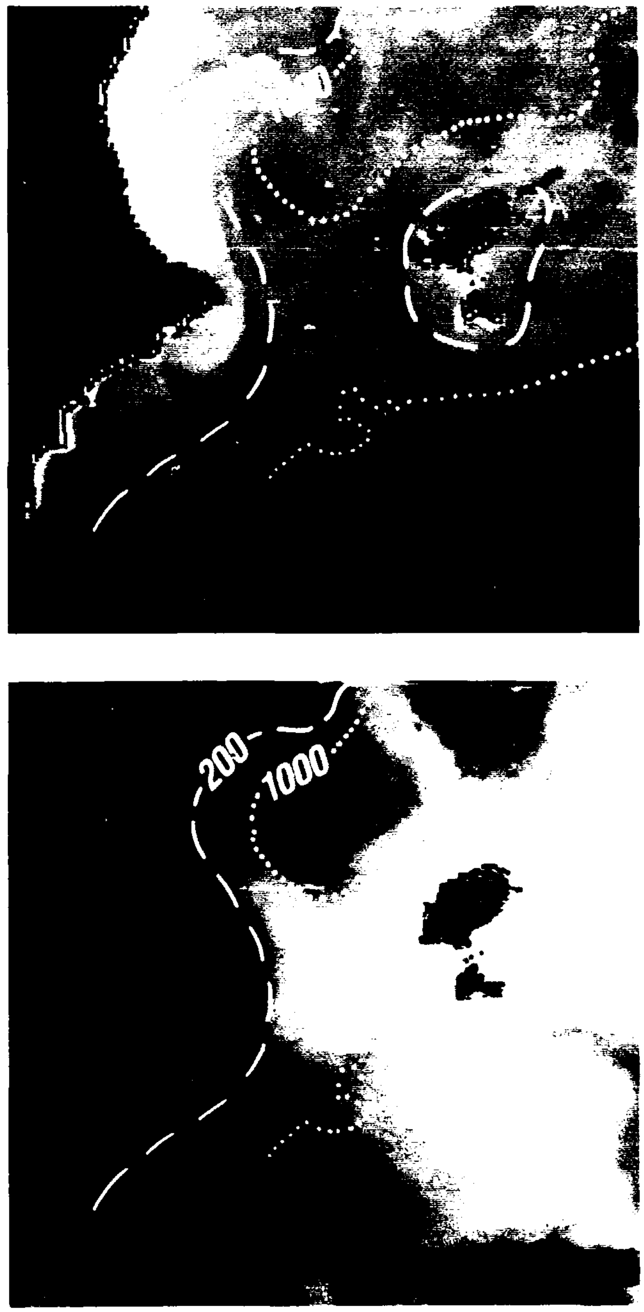

Fig. 4. Thermal satellite imagery for the region between Ibiza and the Spanish mainland showing the Catalan and Balearic fronts. The 200- and 1000-m contours are presented as references to the location of the continental and island slope regions.

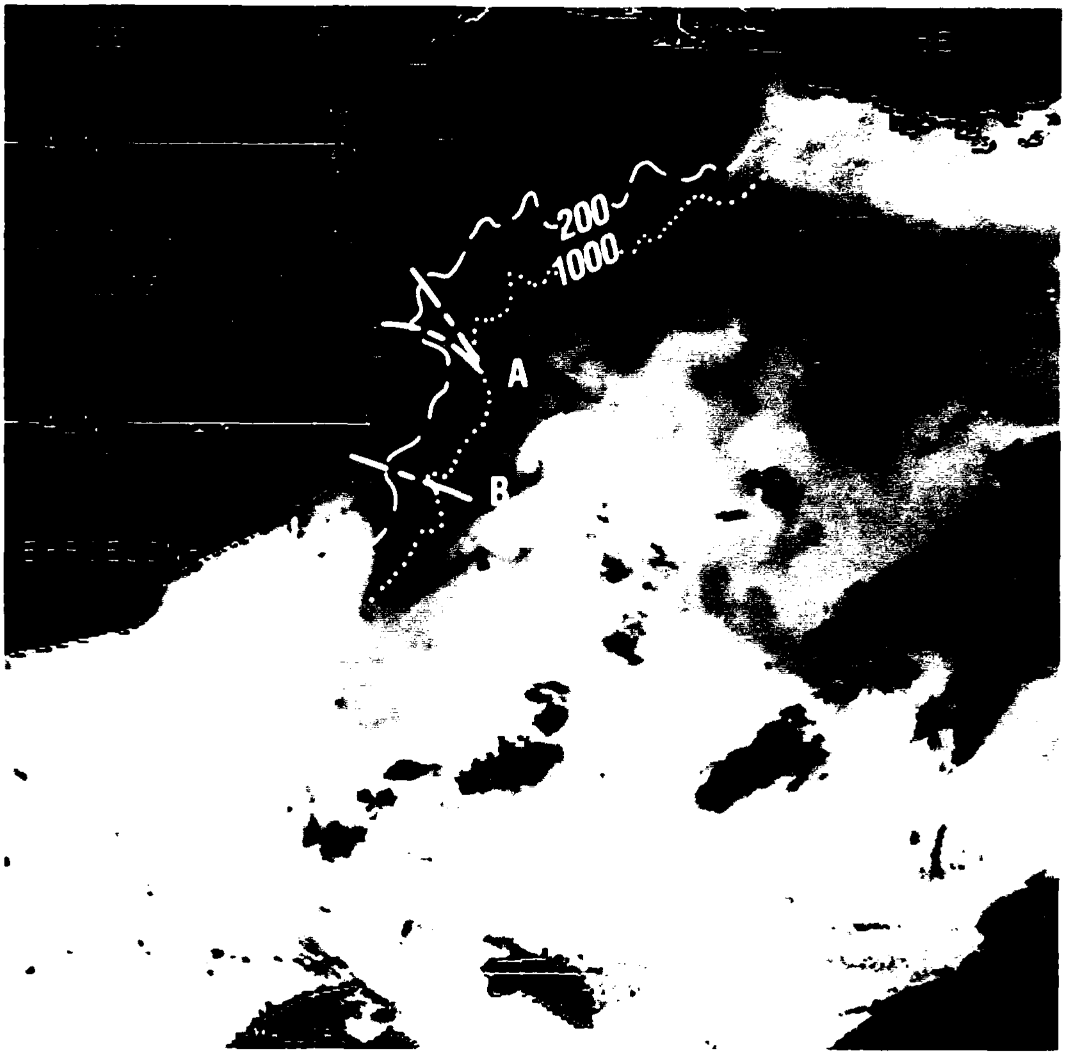

Fig. 5. AVHRR imagery showing the extension of the cool-water plume from the Gulf of Lyons. Note the series of dipole eddies shed by the plume as it proceeds to the south, especially the large pair near submarine canyon D [from *Tintore et al.*, this issue].

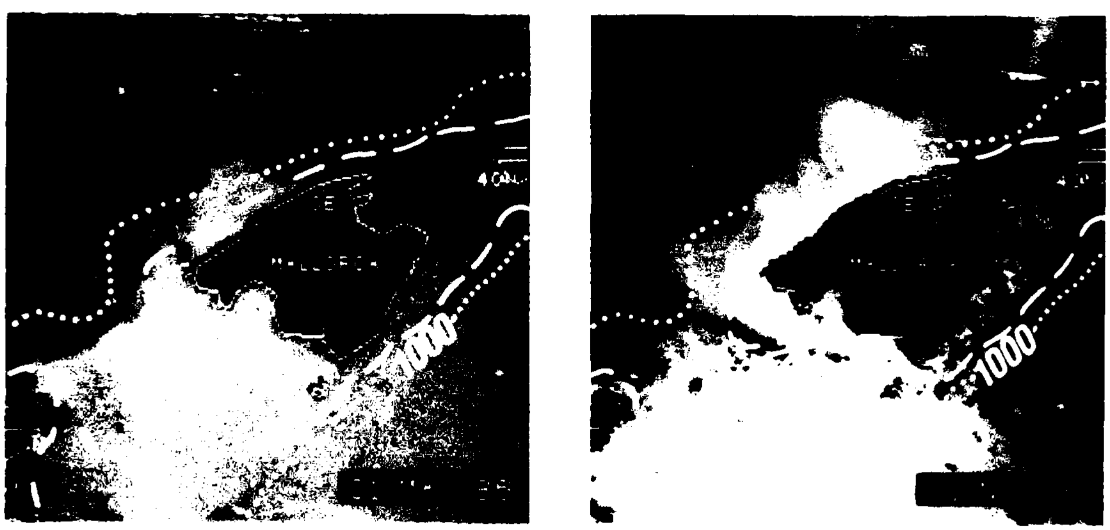

Fig. 6. Representative imagery of the Balearic Front near Mallorca. The 200- and 1000-m contours are presented as references to the location of the island slope region. Despite the wavelike appearance of the front, no advective motion was detectable in any of the imagery of this front.

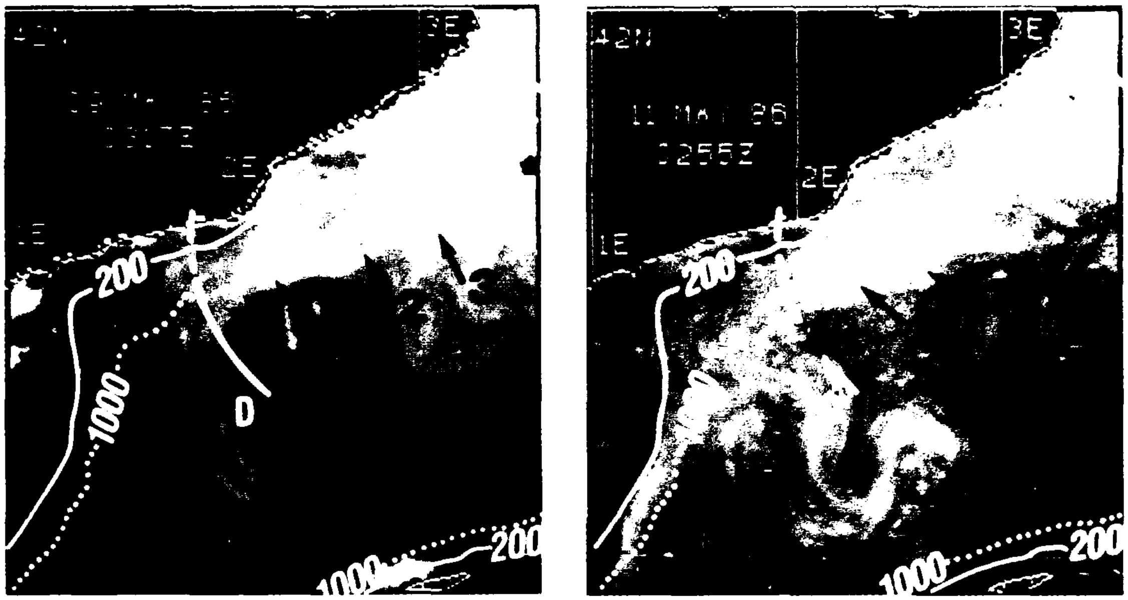

Fig. 7. Thermal features advecting within the Catalan Front (cold water plume). The features indicated by the arrows moved at approximately 20 cm/s and continued into the filament associated with submarine canyon D. During the period May 1–13, the movement of several similar thermal features could be monitored from image to image. During this time, features in the warm water outside the plume and filament showed comparatively little movement. The filament did show some later displacement. However, this movement was much less than the speed of the thermal features inside the filament.

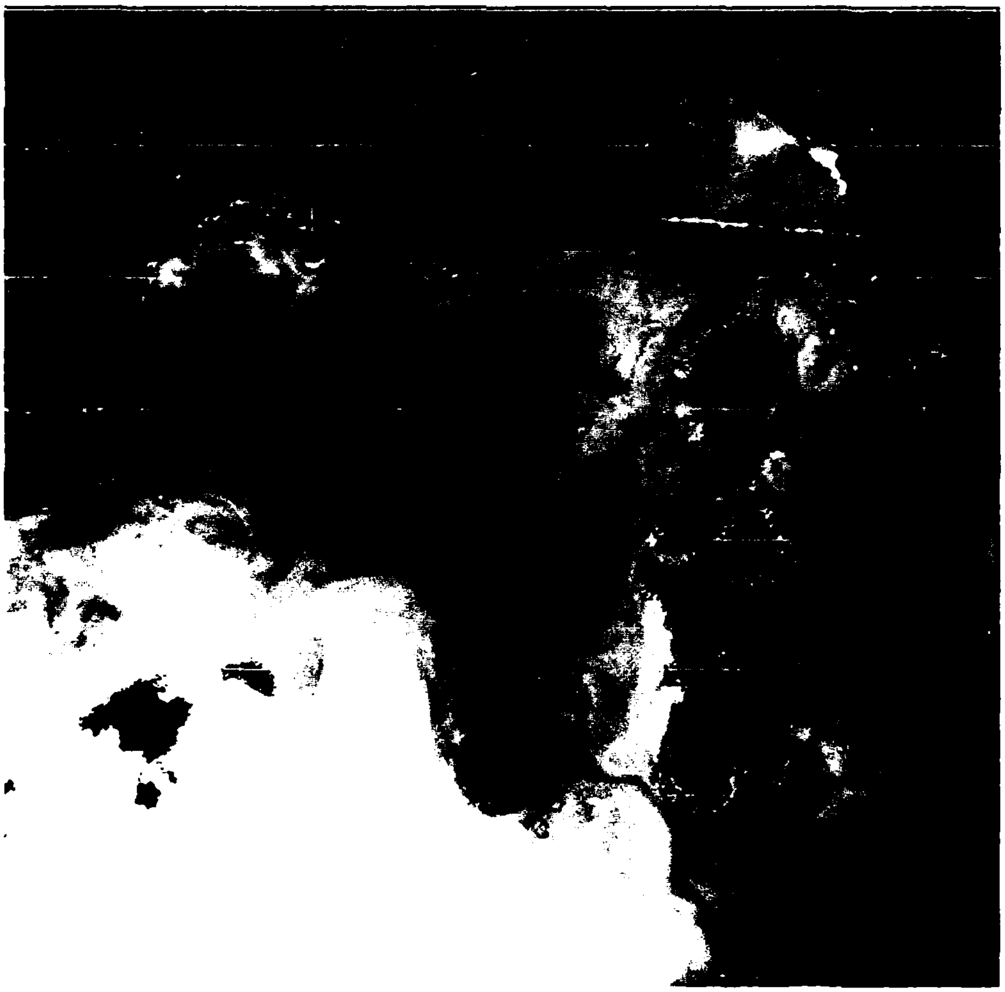

Fig. 8. A thermal image of the northern portion of the western Mediterranean Basin indicating the interrelationship and continuity of the regional circulation of the northern portion of the western Mediterranean Sea (the black mass west of Sardinia is a cloud).

to have a plume of cool water associated with it that originates north of the area. Throughout most of the year, rapidly evolving dipole eddies were observed associated with the leading edge of this plume and the filaments.

3. The Catalan Front frequently spawns energetic filaments that appear to be associated with the plume of cool water. The location of these filaments is closely associated with the location of submarine canyons.

4. The Balearic Front appears to be the least variable and perhaps weakest of the two fronts (this may be because it is the more poorly documented of the two fronts). The front is best seen during summer in the satellite data. The wavelike structure of the front showed no advection in the few image series that were available.

The methodology of this study, i.e., the use of satellite data to expand spatially and temporally limited in situ studies, provides a useful tool for the study of energetic ocean regions that resist normal in situ data analysis. Frequently, as in this case, the satellite data have indicated regions in which more closely spaced in situ data collection would provide the most information on the dynamics of the sea. Hopefully, future studies in the Balearic Sea will include synoptic satellite data as part of both the operational control of the field data collection and as an integral part of the postsurvey data analyses.

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Until recently, the surface circulation of the Balearic Sea has been viewed as largely cyclonic with a fairly quiescent central dome. However, recent studies involving ship data, tracked drifters, current meter moorings, and satellite imagery indicate that this sea has strong mesoscale variability and a more complex general circulation. These studies, together with an examination of registered satellite imagery collected during the Western Mediterranean Circulation Experiment (WMCE), indicate that the surface circulation is strong year-round, and characterized by two permanent density fronts located on the continental shelf slope (the Catalan Front) and the Balearic Islands shelf slope (the Balearic Front). The Catalan Front is the more active of the two fronts. In the northern area, a plume of cold water is frequently observed moving southward along the continental slope region, shedding dipole eddies along the leading edge of the plume. In addition, the Catalan Front continuously spawns energetic filaments that appear to be associated with the plume of cool water. The likely mechanism of formation of these filaments is the deflection of cold water by the regional submarine canyons.

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